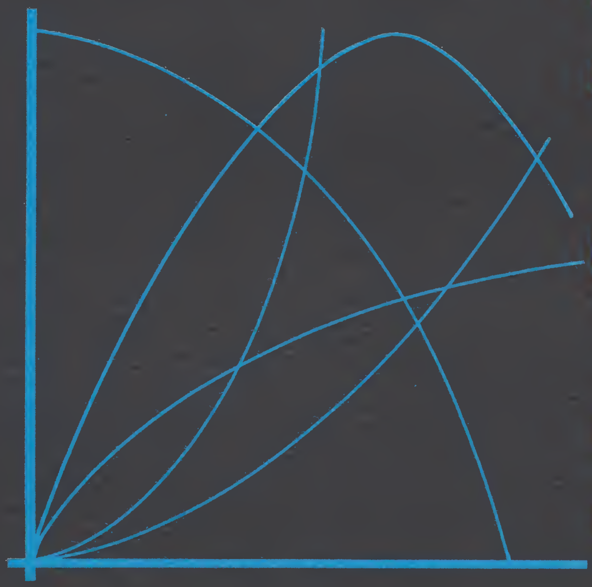
Philbrick Transconductors



"transconductor" (noun) : an active or passive network, the short-circuit output current of which is a specific, accurately known, often non-linear function of the input voltage.

PHILBRICK RESEARCHES, INC.

BULLETIN 6220
SEPTEMBER, 1966

PHILBRICK TRANSCONDUCTORS

THE MATHEMATICAL VERSATILITY of which Operational Amplifier circuits are capable is not obvious if only linear transconductors (i.e., resistance and reactance networks) are used in them. Nor is it extended very far by the addition of *discontinuously* non-linear elements (i.e., diodes, relays, and switches). It is only when exponential, transcendental, and higher-order functions may be generated that Operational-Amplifier circuits are able to *"hold the mirror up to nature"*—for most natural (and many synthetic) processes are neither linear nor quantized, but behave in continuously-smooth nonlinear ways.

PHILBRICK TRANSCONDUCTORS reflect the depth of experience Philbrick brings to bear on all of its analog-system products. As the originators, and the largest manufacturers, of Operational Amplifiers and accessories for them, we were, quite naturally, amongst the first to attempt and achieve practical, stable, accurate networks for the generation of predictably non-linear functions. Our standard Transconductor line is now the largest and most diversified in the industry, and the products it comprises include, we believe, some of the most advanced designs now available.

THE SIMPLICITY AND RELIABILITY of the modern solid-state transconductor network make it as attractive to the equipment designer as the modern Operational Amplifier. Should you require advice or assistance in selecting or applying Philbrick Transconductors, we are eager to place at your disposal the services of our applications engineers, whose collective experience in this field is unequalled.

THE APPLICATION RANGE of accurate, fast, stable, moderately-priced analog transconductors is far wider than is generally appreciated . . . or attempted, we regret to say. Perhaps the exposition in these pages will help to accelerate the rate at which this powerful technique is extended to new areas of circuit and system design. We hope so. Transconductors *deserve* much wider use. The surface is barely scratched.

NONLINEAR ANALOG DEVICES fall into two general classes: (1) those based on the continuous-function characteristics inherent in certain components operating in certain parametric regions, under controlled conditions; and (2) those employing the so-called "straight-line-approximation" technique, (also called "synthesized-function") using networks, built up of many discontinuous (or "gated") branches, so proportioned as to approximate the desired function by a series of straight lines.

INHERENTLY NONLINEAR ELEMENTS. Certain semiconductor junctions exhibit a logarithmic relationship between voltage and current, over quite wide ranges of current. This *inherent* nonlinearity is so useful, that many years have been devoted to the refinement of these logarithmic devices—searching out those that adhere with the greatest fidelity to the formula:

$$e = E_0 \log_{10}\left(\frac{i}{I_0}\right) \text{Volts}$$

over the widest possible ranges of i, and then domesticating them . . . by such means as temperature compensation, etc. The graph below shows the ranges over which typical junctions adhere closely to the straight and narrow (i.e., logarithmic) path.

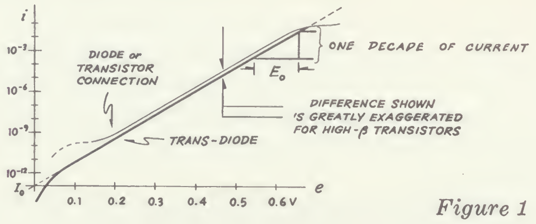


Figure 1

One member of the Philbrick family of "inherent-characteristics" logarithmic transconductors is shown connected in three different ways in the simple schematics below. The graph above, by the way, shows the extended range of accuracy obtained by use of the so-called "trans-diode" connection.

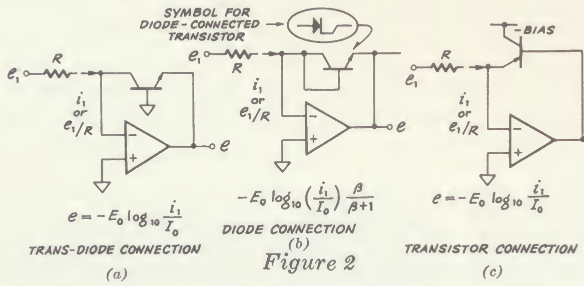


Figure 2

SYNTHESIZED-FUNCTION NONLINEAR ELEMENTS. It is possible to construct a network of elements, not in themselves selected for inherently-conformal nonlinear behavior, but so combined and proportioned as to exhibit the desired nonlinear e/i relationship. Although such synthetic networks are invariably more ramified than are the inherently nonlinear devices, particularly if they must be very accurate, they offer far greater design freedom in the range and variety of available nonlinear functions.

THE PHILBRICK LINE includes accurate networks that exhibit logarithmic, transcendental (trigonometric) and quadratic behavior, and accommodate various combinations of voltage and current polarity. Figure 3, below, shows a simplified generic schematic of such a network. The graphical analysis that accompanies it shows how such a network can be made to conform—at least grossly—to a particular arbitrary function. The input signal, e_1, is connected to n networks, each forming a divider between e_1 and a negative reference voltage, $-E$. The necessary condition for diode conduction in the first branch is $e_1 \geqq \frac{R_{A1}}{R_{B1}} E$ Volts, above which, the current that flows to the summing point (neglecting diode drop) is $i_{D1} = \left(\frac{e_1}{R_{A1}} - \frac{E}{R_{B1}}\right)$Amperes, since feedback from the amplifier (through R) holds the summing point at a virtual ground (zero) potential. Similarly, the necessary condition for conduction of the jth diode is $e_1 \geqq \frac{R_{Aj}}{R_{Bj}} E$ Volts and the current flowing to the summing point via this diode is

$$i_{Dj} = \left(\frac{e_1}{R_{Aj}} - \frac{E}{R_{Bj}}\right)$$

The total current flowing into the summing point is the sum of the currents flowing through each of the conducting diodes. The complete expression for the current flowing into the summing point is then:

$$i = \sum_{j=1}^{n} \left[\frac{\mathbb{U}\left(e_1 - \frac{R_{Aj}}{R_{Bj}} E, 0\right)}{R_{Aj}} \right] \textit{Amperes}$$

where the upper selector operator is defined as:

$$\mathbb{U}(e,\ 0) = \begin{Bmatrix} e \text{ when } e > 0 \\ 0 \text{ when } e < 0 \end{Bmatrix}$$

$\frac{R_{Aj}}{R_{Bj}} E$ is called the jth breakpoint voltage.Reversing the polarity both of the diodes and of $-E$ makes the circuit responsive to negative values of e_1.

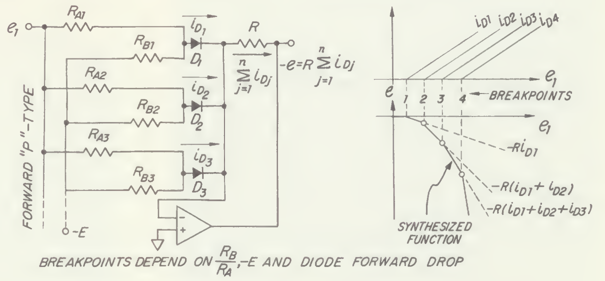


Figure 3

APPLICATION CIRCUITS are summarized on pages 10–11, and treated in greater detail in the Philbrick Applications Manual for Computing Amplifiers, which is described on page 12, under "PHILBRICK PUBLISHES".

PRACTICE

CLASS I—NATURAL CONTINUOUS FUNCTION TYPES (Note 1)

(P) PL1	Dual Logarithmic (Diode or Transdiode)	Note 2
(P) PL2	Quad Logarithmic (Transdiode)	
(P) PL3	Quad Logarithmic (Diode)	
PPL4	Log. w. Temp. Comp.	Note 3
SPL4	Log. w. Temp. Comp. (Built in gain Control)	
SPL4A	Log. w. Temp. Comp. (Built in gain Control and Amplifier)	
SPLR	Log-Ratio (Built in gain Control)	Note 4
SPLRA	Log-Ratio (Built in gain Control and Amplifier)	

Note 1: All standard designs, except (P)PL3, are manufactured in two forms (designated by suffixes "–P" and "–N"), one for each polarity of input signal. In using these designs, it is essential that the associated circuitry accommodate the input/output polarity convention required for the Transconductor. (P)PL3, however can be used with either signal polarity and is, therefore, made in only one form.

Note 2: Pairs of matched basic transconductor elements allow user to achieve effective temperature compensation.

Note 3: Both exponential and linear temperature factors are compensated.

Note 4: Exponential temperature factor is compensated.

CLASS II—STRAIGHT-LINE-APPROXIMATION TYPES (Note 1)

SPLOG	Logarithmic	Note 2
PSQ	Quadratic	
SPSIN	Sine	
SPCOS	Cosine	
SPFX	Arbitrary (adjustable)	

Note 1: All are available in both P & N versions.

Note 2: All are temperature compensated.

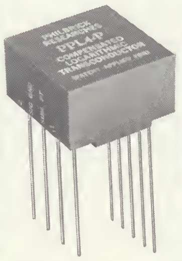
STANDARD TRANSCONDUCTORS may be grouped into two classes (continuous and straight-line approximation) as explained on Page 3. The two classes may then be broken down into a number of families, as shown in the table to the left.

PHILBRICK ALSO MANUFACTURES complete assemblies in which are combined one or more standard Transconductors and the Operational Amplifiers necessary to activate them. (See SPL4A and SPLRA, at left, for example.) Some of the more sophisticated of these assemblies include power supplies, signal-conditioning, scaling, and function-fitting controls, as well. All of them are called "Unit Operators," and they are described in individual catalog sheets, obtainable from your local Philbrick Field-Engineering Office.

SIX PARAMETERS are common to all Transconductors, and their significance should be fully appreciated before any attempt is made to evaluate or predict the performance of a Transconductor or a circuit using Transconductors:

- PERFORMANCE RANGE—states the values of input signal levels for which the specified input/output relationship will be maintained to the specified accuracy. Several ranges are possible, depending on accessories, the amplifier, and the circuit used.
- ACCURACY—is stated in terms of conformance with the specified input/output function. It is frequently given in terms of the maximum per-unit or percent error, under "standard" conditions listed in the accuracy specification, and the error expression is usually a fairly simple function of the input signal level.
- TEMPERATURE COEFFICIENT—relates the (steady-state) ambient temperature to the worst-case error (at equilibrium, all other conditions being standard) in the input/output function.
- RESPONSE ERROR—relates the dynamic (AC or transient) performance of the Transconductor to its DC (steady state) performance; either by stating the (sinusoidal-wave) frequency range over which the "standard-conditions" performance will be maintained, or by stating a slewing rate.
- EXCITATION DEPENDENCE. All transconductors require a near-perfect signal source. When voltage is the independent variable, it should be supplied by the very low closed-loop output impedance of an Operational Amplifier. When current is the independent variable, it should be provided by an Operational Amplifier programmed as a current pump.
- POWER-SUPPLY DEPENDENCE. For best accuracy, transconductors requiring power supply potential(s)—i.e., Class II designs–should obtain them from well-regulated, accurately set supplies; generally, 0.01% absolute accuracy is required to ensure rated performance.
- THREE STANDARD PACKAGES are employed in these designs. They are shown here, in approximately correct relative proportions.

"SP"— STYLE



"PP"— STYLE

"P"— STYLE

TRIGONOMETRIC TRANSCONDUCTORS

THE PHILBRICK SPSIN-P/N AND SPCOS-P/N TRANSCONDUCTORS are Class II (straight-line-approximation) diode-resistor function networks having an output current proportional to the sine or cosine of the applied signal voltage, when used in the recommended Operational Amplifier circuits. All units in this family are scaled to interpret one volt of input as ten degrees of argument. The input range (full scale) is 100°.

These Transconductors lend themselves readily to generating inverse functions (arc sine, arc cosine), over the ranges in which the output is single-valued, and to polar/rectangular conversions. Their inherently high accuracy, speed and stability are maintained over a wide ambient temperature range.

The SPSIN-P produces a *positive* output current (as shown below) when signal voltages of the polarities indicated are applied to its input terminals, A & A′. The SPSIN-N produces a *negative* output under the same conditions; for example, it would *draw* current from the summing junction in the diagram shown. Since the sine of an angle and the angle itself are essentially the same when the angle is small, the useful range of these designs includes small voltages of the opposite polarity; the SPSIN-P, for example maintains rated accuracy for inputs from −1 to +10 volts, representing a range from −10° to +100°. The use of a –P and a –N type in combination will cover the entire range from −100° to +100°.

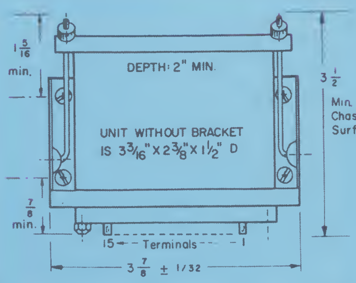
Circuits using these Sinusoidal Transconductors require two "complementary" (equal-but-opposite-in-sign) input voltages (see diagram at right), to generate the required function; they may be derived from a single input by employing a Unity-Gain Inverter to generate the complement. Response curves for the SPSIN-P and SPSIN-N are shown in the application diagram on page 11.

The SPCOS-P and SPCOS-N types are connected in the same manner, to generate cosine functions; however, cosines may be obtained for angles from 0° to 100° with only a single 0 to 10 volt input, as shown by the solid-line curve to the right. The use of complementary inputs provides coverage of the full range from −100° to +100°.

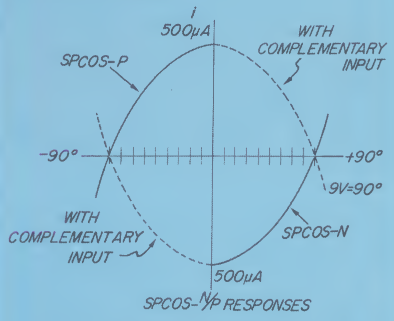
The Applications section (pages 10 and 11) illustrates use of these Transconductors in generating both Sine/Cosine functions and arc sine/arc cosine functions (half range and full range). Additional applications include conversion of coordinate data from rectangular to polar (or polar to rectangular) presentation, the conversion of linear-scale instrumentation to direct angular-function readout, and linearization of signals from rotary-displacement transducers. The theory of operation is given in the text associated with figure 3 on Page 3. A precise 20kΩ, wire-wound resistor is furnished with each unit.

The Transconductors are plug-in modules constructed on a glass-epoxy etched circuit board, with a 15-terminal edge connector. A nickel-plated steel case provides electrostatic and electromagnetic shielding, and acts as a thermal baffle, as well, minimizing thermal gradients. The module occupies a space 3 3/16″ x 1½″ x 2⅜″ above the chassis; a chassis-mounting female socket and hold-down hardware are furnished.

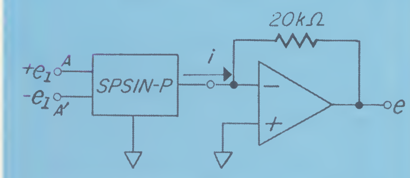
SPSIN-N Sinusoidal Transconductor



DIMENSIONS FOR ALL "SP"—STYLE DESIGNS



SPECIFICATIONS



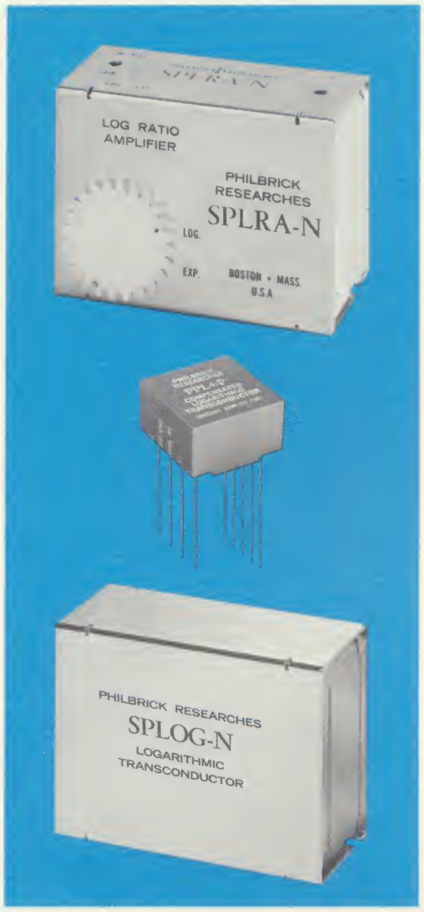
PERFORMANCE RANGE: SPSIN-N/P: −10° to +100° (complementary—i.e., equal but opposite polarity—inputs from −1 Volt to + 10 Volts)
SPCOS-N/P: 0° to 100° (e_1 = 0 to 10V) single input; −100° to +100°, complementary inputs.

ACCURACY: (at 25°C) ±0.1% of full scale

TEMPERATURE COEFFICIENT: <100PPM/°C from −25° to +85°C

RESPONSE ERROR: 5° Phase Shift at 100 kHz. 1 μsec Settling Time to within 10% of final value for any input step up to and including full scale.

LOGARITHMIC TRANSCONDUCTORS



PHILBRICK MANUFACTURES A TOTAL OF TWENTY-TWO DIFFERENT LOGARITHMIC TRANSCONDUCTORS of many different types. All but two (the SPLOG-N and SPLOG-P) are of the Class I, or Natural Continuous-Function Type; the two exceptions, SPLOG-N/P, are of the Class II, Straight-Line-Approximation type.

- One group of ten designs, comprising (P)PL1-P/N, (P)PL2-P/N, and the (P)PL3, are basic non-linear-conductor designs, and require that the user arrange his own temperature compensation.

- A second group, containing six designs (including the PPL4-P/N, and the SPL4-P/N, and the SPL4A-P/N), are temperature-compensated for both linear and exponential temperature factors, and two of them, the SPL4A-P/N also include both amplifiers, and are, therefore, complete function fitters (or "Operators") except for the necessary power supply.

- A third group, containing four designs (including SPLR-P/N and SPLRA-PN) are log-ratio devices (i.e., they produce an output accurately proportional to the logarithm of the *ratio of two inputs*) and are temperature-compensated for exponential temperature factors. The SPLRA-P/N designs include both amplifiers, and are complete operators as explained in the preceding paragraph.

- Finally, the two Class II designs, SPLOG-N/P, are effectively temperature compensated, to a degree compatible with their inherent accuracy They have a dynamic range of four decades.

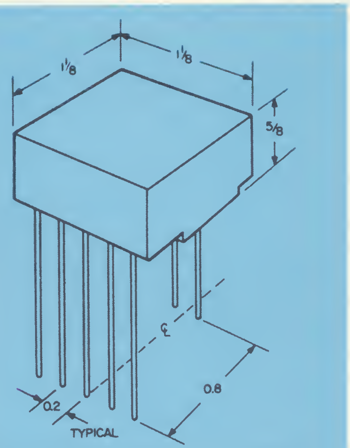
TYPE (NOTE 1)	DESCRIPTION	FUNDAMENTAL e-i RELATIONSHIP AND OPERATING RANGES (Note 2)
PL1-N PL1-P PPL1-N PPL1-P	Dual Element, connectable as diodes, transdiodes, or transistors; uncommitted as to interconnections	$e = E_0 \log \frac{i}{I_0} \simeq$ 60 mV/decade of i 1pA < i < 1mA (9 decades)
PL2-N PL2-P PPL2-N PPL2-P	Quad Element, transdiode-connected, with all four bases connected together, and brought out on one terminal.	$e = E_0 \log \frac{i}{I_0} \simeq$ 60 mV/decade of i 1pA < i < 1mA (9 decades)
PL3 PPL3	Quad Element, diode-connected; uncommitted as to polarity or interconnections.	$e = E_0 \log \frac{i}{i_0} \frac{\beta}{\beta + 1}$ 1nA < i < 1mA (6 decades)
PPL4-N PPL4-P	Temperature-Compensated Transconductor: transistor-connected log element, plus integral current-error and voltage-error compensation	$e = E_s \log \frac{i}{i_s}$ (where E_s is selectable between 0.3V and 2.0V. Nominal value of $i_s = 10^{-4}$A) 10 nA < i < 100 μA (4 decades)
SPL4-N SPL4-P	Same as PPL4 plus built-in gain and current-reference controls	Same as PPL4 (above)
SPL4A-N SPL4A-P	Same as SPL4 plus built-in amplifier	Same as PPL4 (above)
SPLR-N SPLR-P	Log-of-Ratio Transconductor: a pair of transistors as basic log elements, plus dual-purpose current-pump/scaling amplifier. Requires external activating amplifier	See Figure 10 on Page 11, and accompanying text.
SPLRA-N SPLRA-P	Same as SPLR plus built-in amplifier	See Figure 10 on Page 11, and accompanying text.
SPLOG-N SPLOG-P	Temperature-compensated Class II design: fixed breakpoints and slopes. Requires external amplifier	Exponential: $\frac{e}{0.1V} = 10^{-e_1/5V}$ (SPLOG-N*); $\frac{e}{0.1V} = -10^{e_1/5V}$ (SPLOG-P*) Logarithmic: $\frac{e}{5V} = -\log \frac{e_1}{0.1V}$ (SPLOG-N*); $\frac{e}{5V} = \log \frac{-e_1}{0.1V}$ (SPLOG-P*) Range: 0.05 μA < i < 500 μA (4 decades) *(R_{FBK} = 20kΩ)

LOGARITHMIC TRANSCONDUCTORS

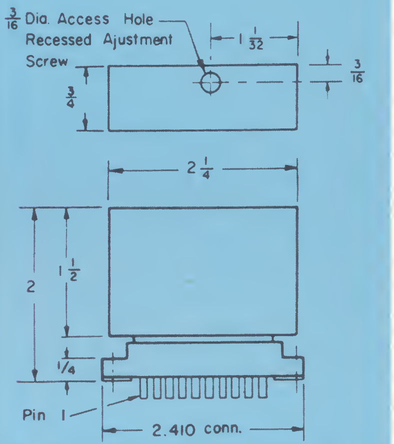
THREE STANDARD PACKAGES are employed in these designs. The smallest is the "PP" style, a cast-epoxy miniature suitable for either plug-in or wire-in mounting on P.C. boards with standard 0.1″ grid spacing. The next larger is the "P" style, a plug-in module, the circuit of which is constructed on a glass-epoxy etched circuit board, with a 15-terminal edge connector, shielded and thermally baffled by a nickel-plated steel case. The largest measures only 1½″ x 2⅜″ x 3³⁄₁₆″ exclusive of terminals, and is called the "SP" style. Its construction is the same as the "P" style, except for the dimensions. Compatible sockets and hold down hardware are supplied with SP packages, and compatible sockets are furnished with P packages.

TYPICAL APPLICATION CIRCUITS for these transconductors will be found on pages 10 and 11. Note that these are referenced in the chart below, where necessary. The theory of operation of the Inherently Non-Linear types is given in the text on page 3 associated with figures 1 and 2. The theory of operation of the Class II (SPLOG-N/P) designs is also given on Page 3, in the text associated with Figure 3.

THE PRACTICAL APPLICATIONS for Logarithmic Transconductors are so numerous and diverse that it is only possible to suggest, in this bulletin, a few of the more obvious ones. First, there are the fundamental mathematical operations (some of which are illustrated on Pages 10 & 11) including log and anti-log generation, log of ratio, raising to arbitrarily-selected powers, extracting arbitrarily-selected roots, computing products and quotients, etc., etc. Then there are the many useful physical-function simulations and electrical measurement and signal-conditioning circuits based upon those fundamental operations: instruments with linear decibel scales; wattmeters; true-RMS meters at the millivolt level—to name but a few. The Philbrick Applications Manual for Computing Amplifiers (see Page 12) is an excellent sourcebook for applications of the Logarithmic Transconductor.



DIMENSIONS FOR ALL "PP"—STYLE DESIGNS



DIMENSIONS FOR ALL "P"—STYLE DESIGNS

DIMENSIONS FOR ALL "SP"—STYLE DESIGNS . . . See Page 5

PERFORMANCE RATINGS @ 25°C	POWER REQUIREMENTS	REMARKS & REFERENCES
See Notes 3 and 4 for accuracy and response ratings. $\lvert V_{BE1} - V_{BE2} \rvert <$ 1mV.	None (activated by associated amplifier)	Lowest-cost precision wide-range log transconductor. See p. 3, figs. 2(a), 2(b), 2(c) for connections.
See Notes 3 and 4 for accuracy and response ratings. All V_{BE}'s matched within 1mV.	None (activated by associated amplifier)	See Figure 2(a), p. 3 for transdiode connection; Fig. 7, p. 10, for typical application & schematic, PL2-N.
See Notes 3 and 4. All diode drops matched within 1mV.	None (activated by associated amplifier)	See Fig. 2(b), p. 3 for diode connection; also Fig. 11, p. 11.
In recommended circuits error is less than ±1% of actual input, over the range from 10^{-4}A to 10^{-8}A.	±15V at 2 mA (nominal)	See Figure 2(c) on Page 3 for transistor connection.
Same as PPL4 (above)	±15V at 2 mA (nominal)	See Figure 2(c) on Page 3
Same as PPL4 (above)	±15V at 9 mA (nominal)	See Figure 2(c) on Page 3
In the recommended circuits, max. (isothermal) error less than ±2% of actual input, over the range from 10^{-4}A to 10^{-10}A.	±15V at 10 mA (nominal) not including activating amplifier	See Figure 10 on Page 11
Same as SPLR (above) over range from 10^{-4}A to 10^{-7}A.	±15V at 17 mA (nominal)	See Figure 10 on Page 11
error in i is less than 0.01% of F. S. output above 5μA error in i is less than 1.0% of actual output, for i below 5μA.	±15V (±0.01% accuracy) at 8.0 mA (nominal).	Fig. 3, p. 3. For moderate-accuracy, moderate-range, high output swing with single amplifier. Recommended ckt.: Fig. 4, p. 10.

NOTES

1. The polarity convention is as follows: In "P" types, current flows **into** the summing point; while in "N" types, current flows **out** of the summing point, when the transconductor is used in a circuit similar to that shown on Page 5. (SPLOG behavior is consistent with this convention).

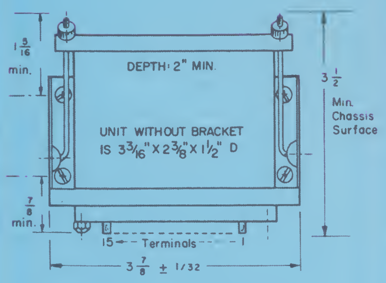
2. **Symbology common to all equations and ratings** is established by the text and drawings on page 3.

3. The isothermal accuracy of these transconductors (over the current ranges indicated) is so high that the errors are almost unmeasureable by conventional means; indeed, they are entirely negligible compared to the error introduced by the input current or voltage uncertainty of the amplifier.

4. The response speed of all Class I logarithmic Transconductors is a complex function of both the external circuit (Including the stabilizing networks) **and** the current range of operation. Consult Philbrick Applications Engineering for specific advice.

QUADRATIC TRANSCONDUCTORS

PHILBRICK PSQ-P/N QUADRATIC TRANSCONDUCTORS are Class II (straight-line approximation) ten-section diode function fitters of the type described on page 3, and illustrated by figure 3. They are designed to produce, to a good accuracy, an output current proportional to the square of the input voltage, when connected (in the circuit arrangement shown below) to an appropriate Operational Amplifier, or a similar null-forcing external configuration. Referring to the schematic, a positive input voltage, e_1, will if applied to input terminal A of a PSQ-P, cause a current i to flow into the summing point. Negative values of e_1 will not produce current in the summing point. Input terminal A′ has exactly the same characteristics. Therefore, if A′ is driven by a voltage equal to $-e_1$, the PSQ will act as a **squarer,** the output current of which is proportional to $(e_1)^2$ regardless of the sign of e_1, since, if e_1 is negative, $-e_1$ will then be positive, and produce output current due to its presence at A′. The PSQ-N differs only in that it *draws* current from (drives a *negative* current *into*) the summing point, when a negative input voltage is applied to either input terminal.



DIMENSIONS FOR ALL "SP"— STYLE DESIGNS

With the circuit shown, the amplifier output voltage, e, is accurately related to the input by:

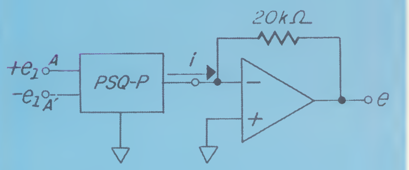
$$|e| = 10\left(\frac{e_1}{10}\right)^2 \ Volts.$$

It is negative for PSQ-P, and positive for PSQ-N. The PSQ-P/N may also be used to extract square roots (in any one quadrant) by using the Transconductor as the feedback element, and driving the 20kΩ resistor with e_1. Under those conditions:

using PSQ-P, $$e = 10\sqrt{\frac{-e_1}{10}} \ Volts \qquad (e_1 < 0)$$

using PSQ-N $$e = -10\sqrt{\frac{e_1}{10}} \ Volts \qquad (e_1 > 0)$$

SPECIFICATIONS



Performance Ranges: 0-10V (either input), 1.2mA max. at 10V. 0-0.5mA output current.

Accuracy (at 25° C): ±0.1% of full scale (error is referred to output when used as a squarer; to input when used as a square-root device.)

Temperature Coefficient: Less than 100 ppm per degree centigrade (0.01%/°C).

Response Error: Phase shift: 2° at 40kHz, 5° at 100 kHz, 45° at 500kHz 1 μsec settling time to within 10% of final value in response to a step input of any value up to full scale.

Power Requirements: ±15VDC at 2.6mA (Voltage stability 0.01%, for best accuracy).

Typical performance of a squarer using the PSQ-P/N is shown on page 10. Applications include: RMS-to-DC converters; circuits for multiplying, dividing, taking square roots, and extracting the square root of the sum of the squares of (any number of) variables; and second-degree series approximation.

The Transconductors are plug-in modules constructed on a glass-epoxy etched circuit board, with a 15-terminal edge connector. A nickel-plated steel case provides electrostatic and electromagnetic shielding, and acts as a thermal baffle, as well, minimizing thermal gradients. The module occupies a space 3³⁄₁₆″ x 1½″ x 2⅜″ above the chassis; a chassis-mounting female socket and hold-down hardware are furnished.

Note that all data given here assumes that the ±15V supply and the 20kΩ resistor are perfect, or that errors introduced by them are negligible. This will be effectively true if the ±15V supply is accurate to ±0.01%, and the resistor has an accuracy of ±.02% absolute. Also, the amplifier gain (open-loop) should exceed 10,000 at the highest frequency of interest.

ARBITRARY—FUNCTION TRANSCONDUCTORS

PHILBRICK SPFX-N/P ARBITRARY-FUNCTION TRANSCONDUCTORS are Class II (straight-line-approximation) ten-section diode-resistor networks, having uniformly-spaced, fixed breakpoints, but permitting convenient adjustment of the slopes of the ten straight-line segments. Used in the recommended Operational Amplifier circuits, they will accept an input voltage and generate an output current proportional to the desired function. The function generated may be, to a good accuracy, any arbitrary, continuous function.

By adjusting a potentiometer in each of the ten network sections (thereby adjusting each of the straight-line slopes between the breakpoints), the over-all response can be made to match the curve representing the desired function, to a good approximation. When necessary, closer approximation can be achieved by incorporating additional SPFX units (having the same polarity gender) to obtain finer subdivision of the curve, or to accommodate functions having arguments of either sign.

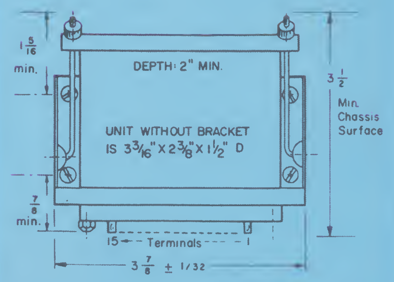
Output-signal scaling is determined by selection of the external feedback resistance. The origin and/or initial slope may be conveniently adjusted when required, by means of external potentiometers. The ten slope-adjustment potentiometers are housed within the SPFX case, and are screwdriver-adjustable.

Separate versions of the SPFX are available for positive-going (SPFX-P) and negative-going (SPFX-N) inputs. One of each may be used in combination, for the generation of functions having inputs of either sign.

As Figure 3 on Page 3 shows, each of the individual networks in the transconductor includes a diode with a voltage divider that determines at what input voltage (e_1) the diode will begin to conduct current into the summing point, when $e_1 \geqq \frac{R_{A1}}{R_{B1}} E$; slope is determined by the value of R_{A1} and an adjustable potentiometer fed by the diode (maximum rate of slope change from breakpoint to breakpoint is 20μA/volt/volt).

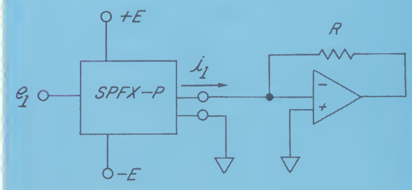
A practical, generalized application circuit (Figure 9) is discussed on page 11. Typical applications include: linearizing of signals from non-linear transconductors; accurate generation of mathematically complex non-linear functions; and simulation of the behavior of complex non-linear physical systems.

These Transconductors are plug-in modules constructed on a glass-epoxy etched circuit board, with a 15-terminal edge connector. A nickel-plated steel case provides electrostatic and electromagnetic shielding, and acts as a thermal baffle as well, minimizing thermal gradients. The module occupies 3³⁄₁₆″ x 1½″ x 2⅜″ above the chassis; a chassis-mounting female socket and hold-down hardware are furnished.



DIMENSIONS FOR ALL "SP"— STYLE DESIGNS

SPECIFICATIONS



Performance Range: With $\pm E = \pm 15V$, e_1 may have any magnitude from 0 to 10 Volts. i_1 may have any value from 0-1mA, provided that no single section is required to contribute more than 0.2mA at $e_1 = 10V$.

Accuracy (at 25° C): May be stated only in terms of the short-term repeatability and long-term stability of the breakpoints and (arbitrarily-selected) slopes, which are of the order of 100 ppm. (.01%)

Temperature Coefficient: (over the range from —25° to + 85° C) approx. 100 ppm per degree centigrade

Response Error: (at typical slope adjustment)—phase error does not exceed 45° at 500kHZ–settling time for .1% error, 1 μsec max., in response to any step input within rating.

APPLICATIONS

BASIC CIRCUIT—LOG OR ROOT RESPONSE. If we connect a nonlinear network or device so that it is driven by the output of an Operational Amplifier, and feeds back a current related to the voltage in a predictably nonlinear manner, the response of the circuit of Fig. 4 (with e_1 connected to e) will be: $e = f^{-1}\left(\frac{e_2}{R}\right)$ *Volts*

where f is the causal functional relationship between the voltage at A and the current into B. This circuit may be used to develop inverse functions. If an exponential (logarithmic) network, such as Model SPLOG-P, is used, the response becomes, for $e_2 < 0$,

$$e_1 = e = 5 \log\left(\frac{-e_2}{0.1\ V}\right) \quad \text{Volts for } R = 20\,k\,\Omega$$

If we had used Model PSQ-N (square-law characteristic), the response of the circuit connected for the inverse function (i.e., square root) would have been:

$$e_1 = e = -10\sqrt{\frac{e_2}{10}} \quad \text{Volts for } R = 20\,k\Omega$$

SQUARER. Here we show the use of a PSQ-P Quadratic Transconductor, which has the basic e, i relationship:

$$i = \left(\tfrac{1}{2} \times 10^{-3}\right)\left(\frac{e_1}{10}\right)^2 = \left(5 \times 10^{-6}\right) e_1^{\,2} \ \text{Amperes}$$

When used as a squarer, e is connected to e_2. The output current of this network is then transduced to a voltage as described on Figure 5.

If e_1 is bipolar, $-e_1$ should be connected to the other input terminal, in order to produce the desired squared output for either input polarity. (Absolute value computation is inherent in the PSQ if both input polarities are supplied.) For positive *output* polarity, use PSQ-N, restricting the current then to *negative* input signals.

LOG OF LOW-CURRENT RATIO. Figure 6 is recommended for obtaining the log of the current ratio at low currents. It employs the transdiode connection, which provides at least two decades more current range than diode connection of the same transistors. The subtractor that follows the two identical log-function circuits then computes the log of the ratio (the difference of the logarithms). Current sources (such as photomultiplier) tolerate larger amplifier input voltage offsets than do voltage sources; therefore, the Philbrick SP2A amplifier is best for current sources, and the SP656 for voltage sources.

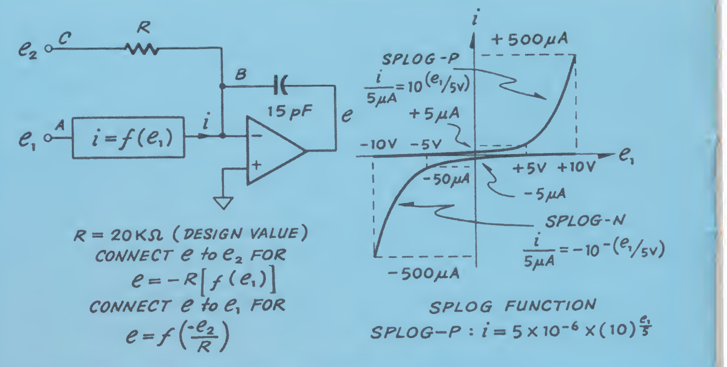


Figure 4

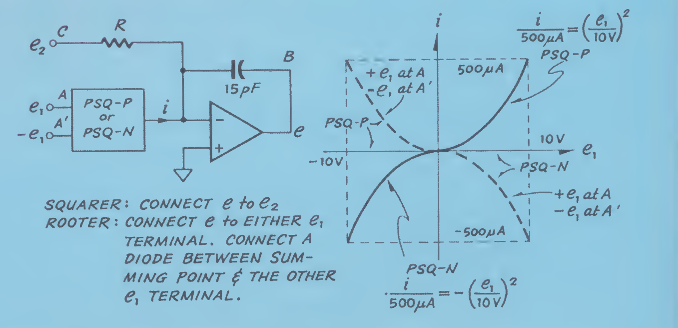


Figure 5

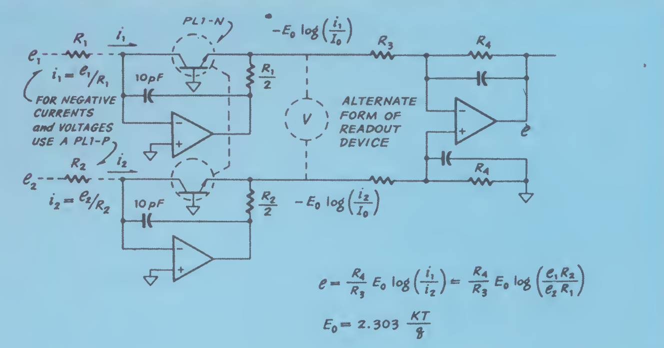


Figure 6

LOG MULTIPLIER CIRCUIT. The circuit of Fig. 7 produces an output of:

$$e = e_3\,(e_2/e_1)^n$$

precisely over many decades, by taking the anti-log of the signal at point A. This signal, e_4, is produced by feeding, to the subtractor circuit in the center of the diagram, the following inputs: (1) the log of e_1, for which it has the gain $(-n)$; (2) the log of e_2, for which it has the gain $(+n)$; (3) the log of e_3, for which it has unity-gain. The exponent, n, is determined by the gain of the difference amplifier. Note that this is essentially a one-quadrant circuit.

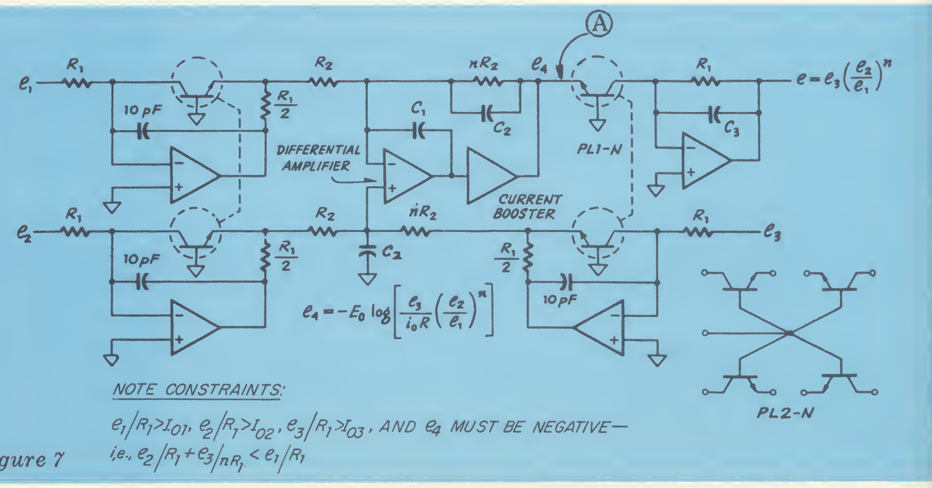


Figure 7

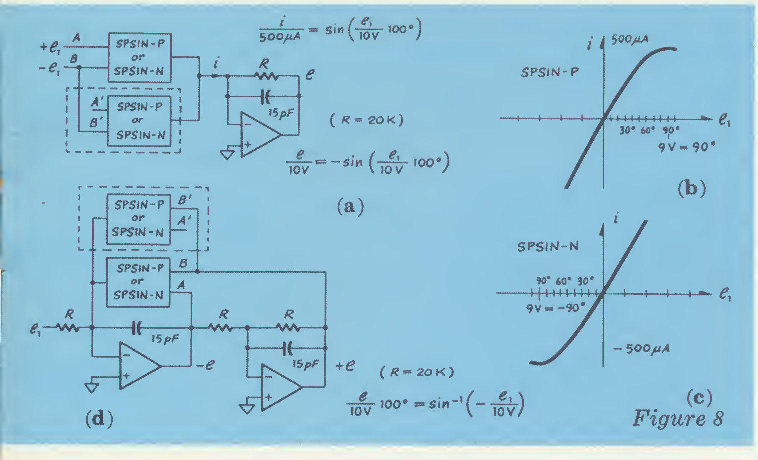


Figure 8

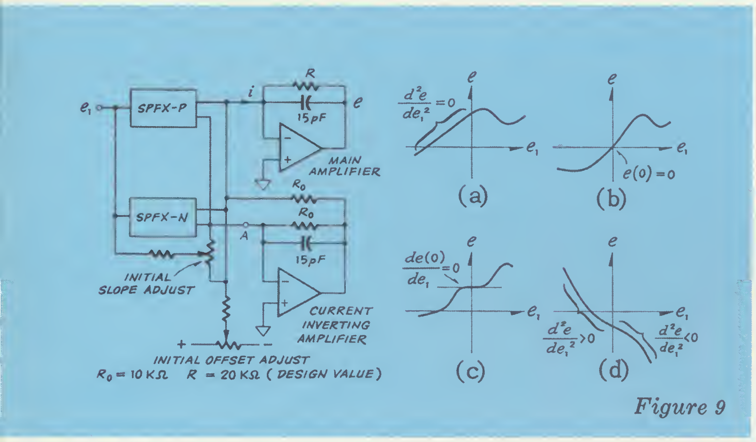


Figure 9

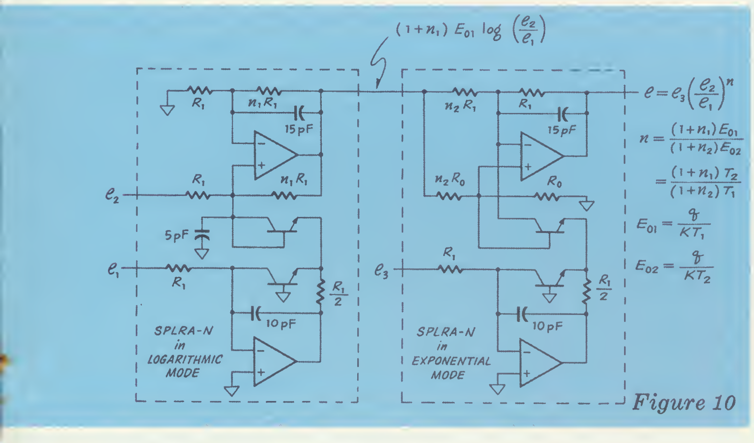


Figure 10

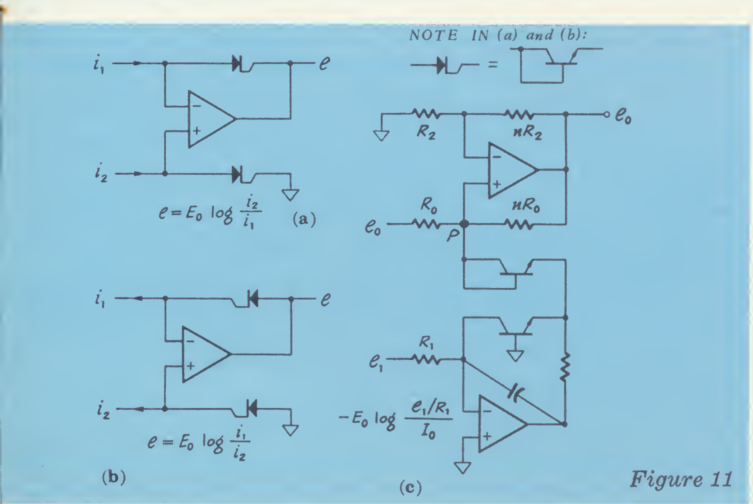


Figure 11

SINE-COSINE TRANSCONDUCTORS SPSIN-P & SPSIN-N have output currents proportional to the trigonometric sine of input voltages. They require two input voltages, e_1 and $-e_1$ (see Fig. 8). Since the sine is nearly the same as the angle itself for small angles, the useful range of the SPSIN-P includes small negative voltages.

By using a P and an N together (additional unit inside dashed line) the sine function can be generated over a range of −100° to +100°. Note that the polarity of the output can be changed by interchanging inputs e_1 and $-e_1$. Generation of the inverse function, arcsine, is shown in the lower schematic. In the conversion of rectangular to polar coordinates, this circuit is the preferred method, for angles less than 90°. Cosine circuits are identical in operation.

ARBITRARY FUNCTION FITTER. SPFX-P has breakpoints for positive-going inputs and SPFX-N has breakpoints for negative-going inputs. The circuit of Fig. 9 generates a function having inputs and adjustable slopes of either sign, and an adjustable origin. If all these degrees of freedom are not required, the circuit can be simplified; e.g., if the desired function has no slope change for one sign of input (Fig. 9a), one SPFX can be omitted. If the origin is at zero, (9b), the initial offset adjustment is unnecessary. For (9c), the initial slope adjustment is unnecessary. Finally, if the desired function has monotonically decreasing slope (negative or zero second derivative) for a positive input and a monotonically increasing slope for a negative input, (9d), the inverting amplifier is unnecessary (ground point A).

LOG MULTIPLIER (USING LOG RATIO CIRCUITS). The Philbrick Log Ratio Amplifiers (SPLRA-P or N) and Log Ratio Transconductors (SPLR-P or N) make convenient "building blocks" for a logarithmic multiplier. The circuit of Fig. 10 shows two SPLRA-N Log Ratio amplifiers connected to give an output

$$e = e_3 \left(\frac{e_2}{e_1}\right)^n \quad Volts$$

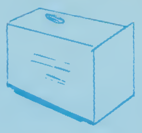
$$where \quad n = \frac{(1 + n_1)\, E_{01}}{(1 + n_2)\, E_{02}}$$

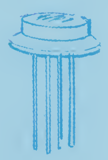
The transconductor version is the same, except that the lower amplifier in each unit must be provided separately.

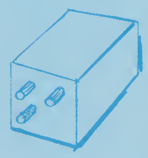
LOG OF RATIO CIRCUITS. Figs. 10(a) and 10(b) show two connections in which one may incorporate a diode-connected dual logarithmic transconductor (such as the (P) PL1-N/P) and, with the aid of a differential amplifier, create an output voltage that is proportional to the logarithm of the ratio of the two input currents. These circuits have the limitation that they will operate only with unidirectional *currents*. Circuit (c) shows how to obtain the log of the ratio of two input *voltages*. The lower amplifier computes the logarithm of the numerator and the upper amplifier functions as a current pump that injects a current proportional to the denominator. The difference between the diode voltages (the log of the ratio) appears at "P" and is magnified by the gain ratio $(1 + n)$.

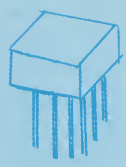
$$\underset{(at\ P)}{e} = -(1 + n)\, E_0 \log \left[\frac{e_1/R_1}{e_0/R_0}\right] \quad Volts$$

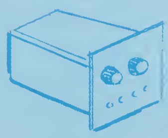
Philbrick in Miniature . . .

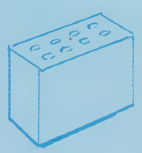


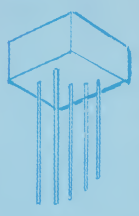


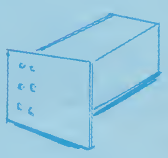












PHILBRICK IS . . .

A perennial pioneer, having invented a good many of the analog techniques that are now universally applied. A perennially-youthful creativity, stimulated by a passionate need to lead, has kept us far ahead of the pack.

An able assembly of engineer-scientists, working in an intellectually-democratic environment that manages to nurture the scientific method without devaluing empiricism . . . or any other respectable route to the required result.

A customer-conscious organization that has learned the wisdom of taking the long view. Time and effort are *never* rationed when a customer—any customer —needs help that is within our ability and power to give.

A sound, substantial, publicly-owned company, incorporated in 1946, after a decade of computational research. The first to offer commercial analog building blocks and systems, our growth has been sustained and healthy throughout our twenty-year history. Our D & B rating: AaA 1.

PHILBRICK SERVES . . .

Its customers in many ways—including, but not limited to, the following:

APPLICATIONS ENGINEERING—by a large and well-informed staff of engineering specialists, whose primary concern is to assist in the application of the Analog Way. We are proud of their objectivity—a quality we consider essential to our success as well as yours.

They are authorized to accept a reversed-charges telephone call from anyone, anywhere in the country.

FIELD ENGINEERING—We employ over 100 professional field-engineering representatives throughout the world, to provide rapid, informed, on-the-spot assistance in matters that may not be efficiently handled by telephone communication or correspondence with our Applications Engineering Department. Most Philbrick representatives have been associated with the company for many years, and have become expert in applying Philbrick products.

EDUCATIONAL CLINICS—a series of interesting, and practical seminars and clinics in Operational Amplifiers, Computing and Simulating, and Instrumentation . . . either at the beginner's level, or in a form designed for the advanced and experienced specialist.

COMPUTATION CENTER—Our goal remains unchanged over the years; to marry operational concepts with electronic technology in pioneering new instruments and computing systems. Toward this end, we solicit and welcome the opportunity to consult with you, without charge. Consulting services on a more formal, fee basis are also available.

PHILBRICK MAKES . . .

The most numerous, most advanced, and most diversified line of Operational Amplifiers on the market, employing all three of the prevailing component technologies. Most are discrete-component, solid-state designs; a few reach forward into the integrated-circuit realm; some draw upon the best of the still-potent vacuum-tube art. We manufacture every important *kind* of Operational Amplifier, (over 100 Models, in a dozen different basic forms, some exclusively ours).

Several different families of system-building apparatus, complete analog-function assemblies, arbitrary-function generators, universal linear and non-linear operators, multiplier-dividers, and "uncommitted" manifolds; also the Q3 Modular Packaging System —a refreshingly-new approach to "packaging" instruments or system elements of your own design.

The widest array of operational components and accessories in the industry, including Transconductors —conveniently packaged, scaled, and biased non-linear circuits for generating sine and cosine functions, and logarithmic, root, and exponential responses. Also, high-performance DC power supplies, in many forms and ratings. We can furnish just about any kind of circuit, component, and accessory, from the humblest hardware to the most sophisticated network, that may be required.

PHILBRICK PUBLISHES . . .

Almost every kind of printed communication, ranging from the massive Applications Manual described below to dozens of informal Applications Briefs. We believe that a complete set represents the largest collection of empirical and theoretical data on the Analog Art ever assembled. Included are . . .

APPLICATIONS MANUAL FOR COMPUTING AMPLIFIERS. This manual is the crowning achievement of 20 years of commentary on, and exposition of, the Analog Way. Lovingly collected, profusely illustrated, and minutely described, the hundreds of circuits treated provide a panoramic portrait of the current state of the art . . . and some of its past triumphs, as well.

CATALOGS. Philbrick Amplifier literature includes not only detailed descriptions of each of the 18 basic amplifier families—their mechanical and electrical specifications, operation and installation notes, and other such routine data—but also a wealth of specific installation and operation advice.

Catalog information of the same quality and detail has been prepared for Philbrick Transconductors, Computation Modules, Accessories, Structures, and Computing Systems.

THE LIGHTNING EMPIRICIST. A much-respected, widely-read quarterly publication, is sub-titled "Advocating Electronic Models, At Least Until Livelier Instrumentalities Emerge". It will be sent to you, upon request, if your interests and activities make it of value to you.

The famous Philbrick Solid State Amplifier Chart is, if nothing else, a miracle of condensation. It somehow contrives to compress most of the *essential* data on over 75 Philbrick solid-state amplifiers into a mere 24" x 11". It is indispensable to anyone wishing to purchase an Operational Amplifier (of any kind). If your facility has frequent use of such information, request it in wall-chart form (48" x 22").

PHILBRICK RESEARCHES, INC.

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TEL: (617) 329-1600 TWX: (617) 326-5754

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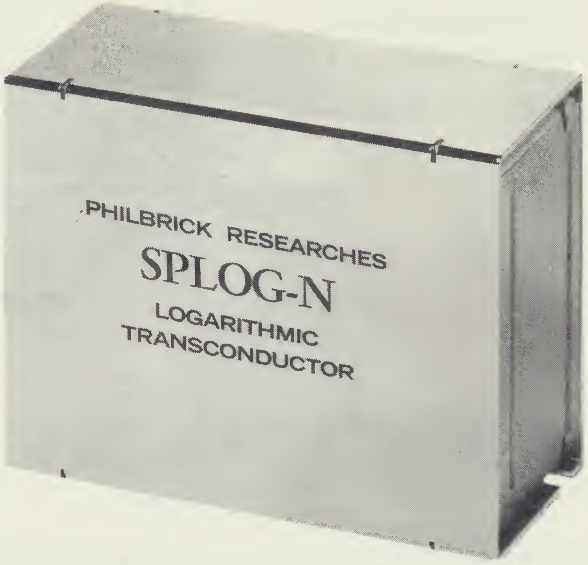
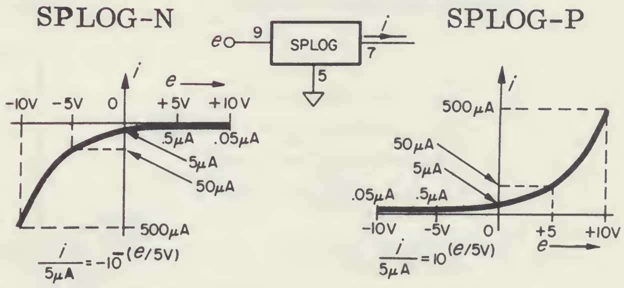
PHILBRICK

Models SPLOG-P and SPLOG-N Logarithmic Transconductors



Models SPLOG-P and SPLOG-N are temperature compensated 12-segment diode function generators of which the logarithm of the output current is proportional to the input voltage. Model SPLOG-P is designed to feed a positive current into the low impedance presented by the summing point of an operational amplifier, while Model SPLOG-N transduces a current in the opposite sense. A fine trim of the slope of the eight most critical segments is provided by factory adjusted potentiometers. The remaining four least critical segments have non-adjustable slopes. Only hermetically sealed silicon semi-conductors and metal film or carbon resistors are used for best reliability and lasting accuracy.



TRANSFER FUNCTION

SPECIFICATIONS

ELECTRICAL

INPUT: -10 V to +10 V @ 50 μA maximum (2.5 mA maximum transient)

OUTPUT: $1/2 \times 10^{-7}$ A to $1/2 \times 10^{-3}$ A

RESPONSE: For output currents > 5 μA the equivalent circuit (as viewed from the summing point terminal) can be approximated by an incremental resistance value

$$R = \frac{de}{di} = \frac{5 \log \epsilon}{i} = \frac{1}{0.46\, i}\ \Omega$$

(e = input voltage, referred to summing point potential

i = output current at summing point terminal)

shunted by approximately 3 pF and for output currents <5 μA the equivalent circuit can be approximated by the same incremental resistance shunted by approximately 9 pF.

POWER REQUIREMENTS: ±15 VDC @ 8 mA maximum, with ±.01% voltage stability required for best accuracy.

ACCURACY (@25°C): For output currents >5 μA

$$\left|\frac{\Delta i}{i_{desired}}\right| < 0.01$$

For output currents <5 μA

$$\left|\frac{\Delta i}{i_{max}}\right| < 0.0001$$

where $\Delta i = \left(i_{actual} - i_{desired}\right)$

CONFORMITY VS. TEMPERATURE

Tabulated Value / Temperature	Output Currents > 5 μA $\left\|\frac{\Delta i}{i_{desired}}\right\|$	Output Currents <5 μA $\left\|\frac{\Delta i}{i_{max}}\right\|$
-25°C	0.01	0.0002
0°C	0.01	0.0002
+25°C	0.01	0.0001
+55°C	0.02	0.0005
+85°C	0.03	0.001

TEMPERATURE: -25°C to +85°C operating.

TERMINAL DESIGNATIONS:

1 N.C.	6 Key	11 N.C.
2 -15 V	7 Sum. Point	12 N.C.
3 +15 V	8 Power Com.	13 N.C.
4 N.C.	9 Input	14 N.C.
5 H.Q. Ground	10 N.C.	15 Shield

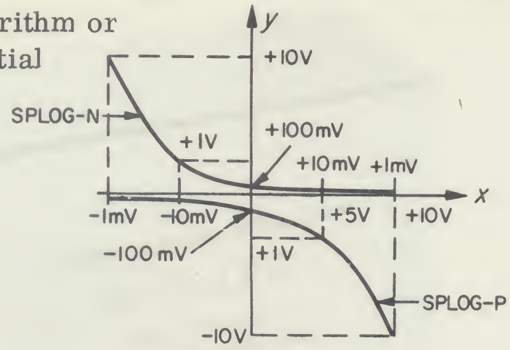
MECHANICAL

All components are assembled on a glass-epoxy etched circuit board with edge connector, which in turn is mounted in a nickel plated steel case. A socket for the edge connector and hold-down hardware are supplied.

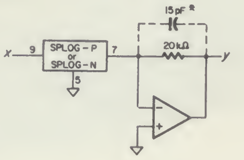
BULLETIN SPLOG-P/N/1B1 June 66

APPLICATIONS

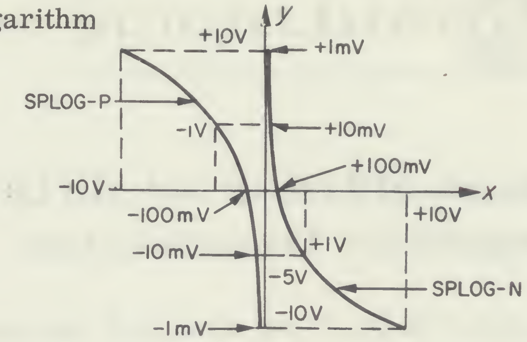
1. Antilogarithm or Exponential



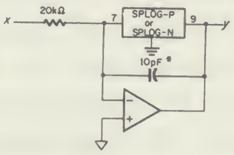
✱ Choice of capacitor depends upon amplifier characteristics



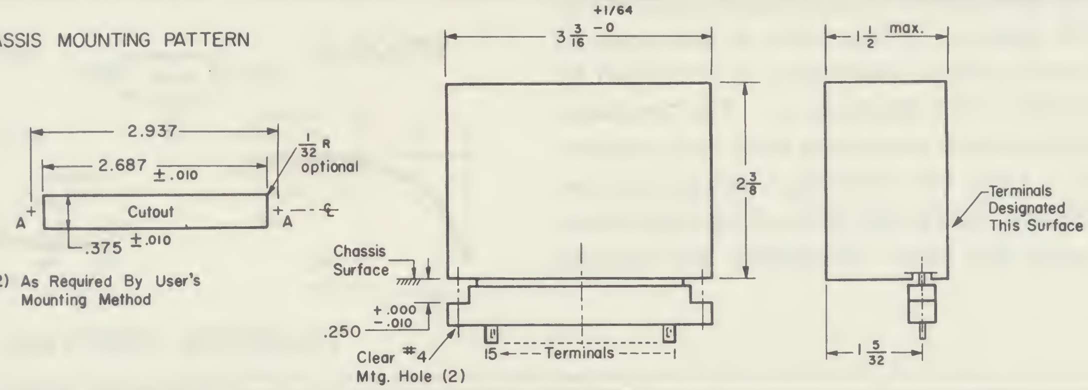
2. Logarithm



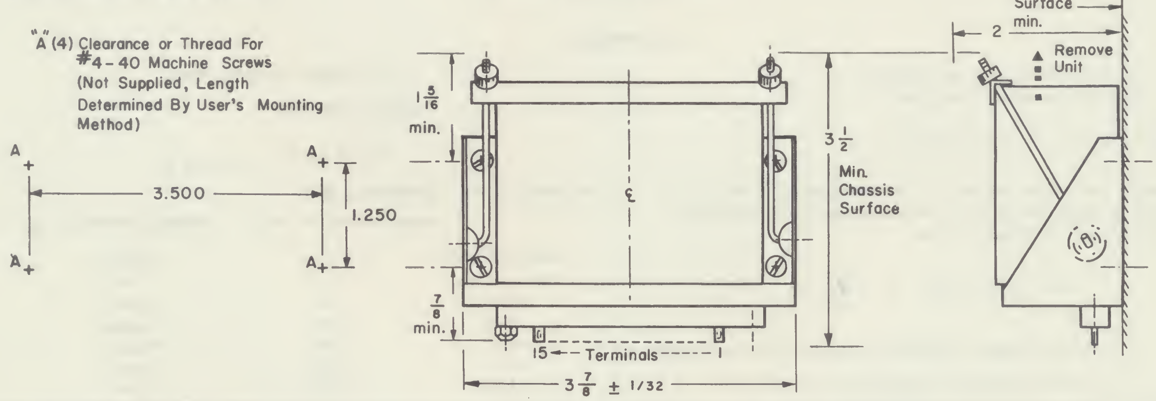
✱ Choice of capacitor depends upon amplifier characteristics



CHASSIS MOUNTING PATTERN



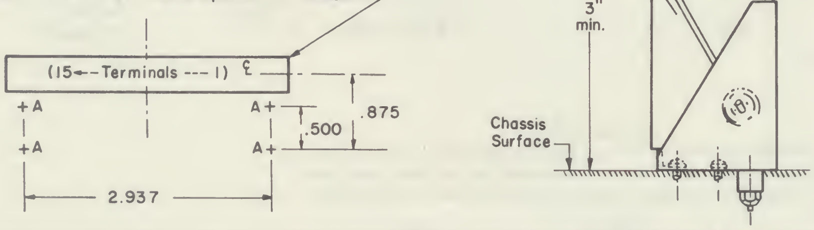
HORIZONTAL MOUNTING



VERTICAL MOUNTING

"A" (4) Clearance Or Thread For #4-40 Machine Screw (Not Supplied)

Cutout: .437 X 3 3/8 ; 1/32 R. Optional At Corners



Note
1. Connector Supplied.
2. Mounting Bkt. Steel, .036 Th'k.
3. Connector Is Floating When Mounted To Bracket. DO NOT ATTEMPT TO TIGHTEN CONNECTOR MOUNTING SCREWS

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